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The Effects of Specimen Edge Conditions on Heat Release Rate

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When bench-scale specimens are tested for heat release rate, it is generally of interest that the behavior of the specimen simulate, as much as is possible, that of a real-scale product performing in a real fire. A number of issues have been raised recently by workers trying to understand the optimal conditions of specimen preparation and mounting. In the present study a large number of materials were explored in the Cone Calorimeter to determine the effect of edge conditions and edge frames. It was found that by the use of an insulated edge frame, heat release rate values can be obtained which are slightly closer to expected true values. The testing procedure, however, is significantly more complicated. This makes the insulated edge frame useful for collecting specialized data for fire modeling, but not for conducting routine reaction-to-fire tests. For routine testing use, it is recommended: (1) that no edge frame needs to be used unless the test specimen presents special difficulties, such as due to intumescence; (2) that in those cases where the use of the steel edge frame is found necessary, the results should be reported on the basis of an effective exposure area of 0.0081 m². When reported on such a basis, the heat release rate results do not show a systematic bias, compared to results with no edge frame.

INTRODUCTION

The objective of bench-scale heat release rate (HRR) testing is normally to be able to predict the HRR of real-scale products, without having to conduct expensive, time-consuming real-scale tests. It is obvious that a reduced-scale test—of any type—can never be an exact representation of a larger-scale reality. However, for HRR data to be meaningful and useful, it is important that the representation be as good as is currently possible, consistent with other objectives. For instance, one should not propose specimen-preparation techniques which, while improved, would be unduly difficult or costly, or require exceedingly skilled personnel. It is the view of the authors that the whole area of optimization of specimen preparation is still in its infancy. We generally know best how to prepare specimens which are 'well-behaved'. Specimens which present mechanical difficulties during testing require tailor-made solutions. Such solutions tend to emerge only when there is an active enough research area in a particular class of polymers, composites, etc.

The immediate motivation for the present study comes from two studies, one made by Toal and co-workers and the University of Ulster[1,2] and the second by Urbas and Sand at BASF[3]. Both of these studies were made using the Cone Calorimeter (ASTM E 1354[4]; ISO 5660[5]). Toal tested several materials with and without an aluminum foil wrapping of the specimen and with and without an edge frame. The standards prescribe that, for all cases except calibrations with PMMA, the specimen is to be wrapped with aluminum foil on the sides and bottom. The purpose of the aluminum foil is to eliminate mass transfer along all boundaries except for the burning face of the specimen. If a foil were not used, pyrolysates or molten material could flow from the specimen into the refractory fiber blanket supporting the specimen. Also, active burning would be more likely to take place along the sides of the specimen; they would also not be shielded against the (unintended) heating from the cone heater. By contrast, the only drawback associated with the use of the aluminum foil is a heat sink effect, but this is very small due to the low mass of the foil. The case of the calibration PMMA specimen, which is prepared without aluminum foil, is discussed in detail in reference 6. In this study, we will not further address Toal's findings with regard to omitting the aluminum foil, since we consider that, in general, such non-standard test conditions would violate the basic requirement of minimizing mass transfer on all sides save the burning face.

The two test standards both describe a stainless steel edge frame. Under the ASTM standard, its use has been left to the discretion of the laboratory; ISO, however, have recently put its use as a mandatory item. The steel edge frame (Fig. 1) was designed for use under three conditions:[7] (1) when materials are prone to show excessive flaming along the edges; (2) when needed to hold together a multi-layer specimen which may be prone to delamination; (3) to retain the metal grid. The last is another optional feature of the test. Certain materials and products exhibit a high degree of intumescence when exposed to a heating flux. If such materials were allowed to expand without limit, mechanical difficulties would result as the material contacted the spark plug or the cone heater. Furthermore, a material with such greatly expanded surface area would be receiving an ill-characterized radiation, over an ill-defined exposed area. Thus, a grid made of wires, punched metal, or other equivalent means, is used in such cases to limit the amount of specimen deformation. The grid itself has to be retained in some way—for this purpose the use of the edge frame is prescribed.

Toal's findings were that use of the edge frame on fiberboard specimens reduced the peak HRR and lengthened the burning time. This is consistent with findings at NIST,[7] where an edge frame (or equivalent means) was seen necessary with almost all samples made of wood or other cellulosic materials.

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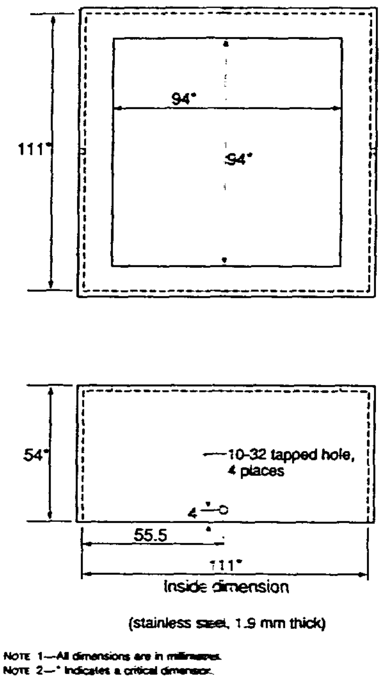

Figure 1. Steel edge frame, as described in ASTM D 1354 and ISO 5660.

More interesting were the results reported by Urbas and Sand. These workers were concerned that the standard steel edge frame, in addition to serving to restrain a specimen and quench any edge flaming, might also be a substantive heat sink. They designed an alternative edge frame, comprising an insulating collar made of medium- or high-density refractory material. Their conclusion was that the best edge condition was an insulating frame which most closely approximates the specimen in thermal properties. Specifically, they suggested that such an edge frame would be a better choice even in cases where no edge frame would normally have been utilized. Such an approach raises some very interesting questions, which the present study is intended to answer.

The study was intended to examine these issues further and to enable definitive recommendations to be made. For our study, an irradiance of 50 kW m^{-2} was selected since, our experience suggests this is high enough to evince problematic behaviors from specimens with such tendencies, but not high enough to cause excessively fast burning.

THEORY

The basic analysis of bench-scale HRR data proceeds from the way that such data are used. To derive the real-scale HRR, we envision the real-scale combustible as being divided into numerous finite elements, each Δx by Δy in size. Then, one must first predict in the real scale when flame spread will reach each area element, then integrate the per-unit-area HRR over the burning area of the real-scale combustible. For most cases, we expect the irradiance and HRR variations, along the surface of the real-scale object to be only slight. In such cases, if we ignore these variations, this is equivalent to requiring that a *plane of symmetry* be passed anywhere through that surface, including at the edges of each finite element. By definition of a plane of symmetry, there can be no heat or mass transfer across such a boundary. Thus, we reason that the ideal testing condition is for each of the bench-scale specimen's sides to be adiabatic and to have no mass transfer.

EXPERIMENTAL

A wide variety of specimens were tested under at least three different test conditions: foil-only, standard stainless steel edge frame, and insulated edge frame. The test materials were chosen to include both cellulosics and thermoplastics as well as a number of products which are known to present difficulties in testing.

The experimental insulated edge frame

Urbas and Sand did not address in their work the main reason for using an edge frame: that it is needed to hold down either the specimen or a metal grid. In the present study, we explored this aspect by designing a different insulated edge frame, one which can both retain the specimen itself and a metal grid. Figure 2 shows the experimental insulated edge frame assembly. The holder was designed to accommodate specimens from approximately 6–50 mm thick. The assembly comprises two main pieces–the insulating fiberboard collar, and an outer stainless steel edge frame. The insulating fiberboard collar is made from a rigid, 180 kg m^{-3} ceramic fiberboard, and contains a central 101 × 101 mm opening for specimen insertion. The depth of this collar is 25 or 50 mm,

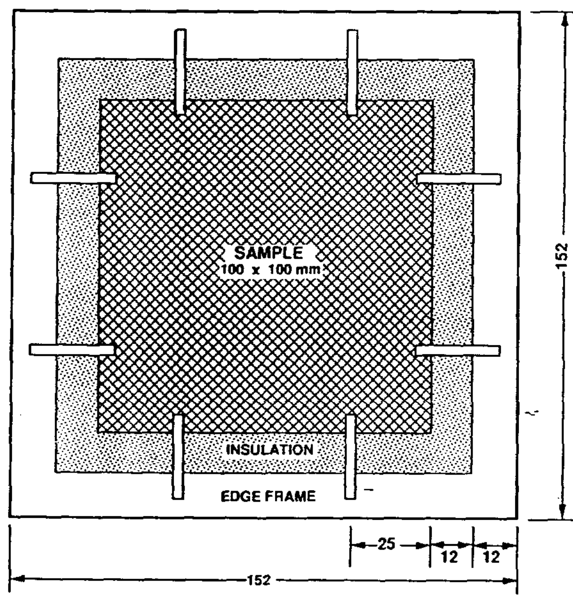

Figure 2. Experimental insulated edge frame assembly (all dimensions in mm).

depending on the product being tested. The outer steel edge frame has two metal 'teeth' along each edge. These serve to restrain the specimen, or to retain the metal grid. The outer frame also has 'legs' at the sides (not shown). The normal specimen holder has been modified with fixing studs on the edges; the legs from the outer frame engage these studs and are bolted down. This ensures that the outer frame does not rise or move during testing. The material underneath the specimen is the same 65 $kg\,m^{-3}$ blanket as is specified in normal testing. To use the holder, the specimen is first wrapped in aluminium foil, then it is inserted down into the collar. This assembly is then placed atop the horizontal specimen holder. Finally, the outer steel edge frame is placed on top and bolted onto the sides of the specimen holder.

Reduced size specimens

To explore the effect of specimen area, seven of the materials were also tested in a reduced-size (75 × 75 mm) configuration. For this purpose, a modified insulated edge frame was made up. This frame differed from the one shown in Fig. 2 by the fact that an opening of only 76 × 76 mm was provided in the center. Appropriate 'teeth' were not installed for this configuration, so only specimens not requiring top-down restraint could be tested this way.

Procedure

Ten different materials were tested in the horizontal orientation at an irradiance of 50 $kW\,m^{-2}$ for the reason already given. Each material was typically tested in three different sample holder configurations. While in a few cases three test runs were made, in most cases only two test runs were done at each test condition. This was motivated by the desire to explore more materials, which was felt to be more valuable than improved accuracy of result for any one material. Other than the variations described, the testing was conducted as required by ASTM E 1354.

Standard size samples

(1) The sample simply wrapped in aluminium foil and set on the sample holder pan.
(2) The sample wrapped in aluminium foil and set on the sample holder pan using the standard stainless steel edge frame (hereafter referred to as the 'steel frame').
(3) The sample wrapped in aluminum foil and inserted into the experimental insulated edge frame described above ('insulated frame').

All samples were placed on a layer of insulating fiber blanket at least 13 mm thick.

Reduced-area samples To be able to explore more directly the effect of specimen area, certain tests were repeated with a reduced-size specimen. The specimens, in these cases, were of 75 × 75 mm face dimensions, with the specimen thickness unchanged as from above.

Temperature measurements In order to examine the temperature profile across the surface of the specimen during the test, 0.127 mm (5 mil) Type K thermocouples were attached at the center, edge and midway between the center and the edge for three of the materials tested in the reduced-area configuration. Because of the strong dependence of the pyrolysis rate on the temperature, these measurements give a qualitative indication of how the mass loss rate varies across the surface as well as a qualitative indication of how the heat flux from the flame varies across the surface.

Test materials In the list below, the materials are identified and the basic reason for its selection is given. Except as stated in detail below, the foams were all commercial materials of undisclosed formulation.

(1) PMMA
Thickness 25 mm
Density 1160 $kg\,m^{-3}$
Black color, from Rohm & Haas.[a] This is the old version of a PMMA material which used to be used for Cone Calorimeter calibrations. It was chosen since it is a very well-behaved material and tends to show a nearly-constant heat release rate.
(2) Particle board
Thickness 12–13 mm
Density 640 $kg\,m^{-3}$
This material was used because there was a substantial amount of experience in testing it for the ASTM round robin on the Cone Calorimeter.[4] It was specifically selected since it has a tendency to burn along the edges. It also shrinks drastically (about 20%).
(3) Oak wood blocks
Thickness 32 mm
Density 735 $kg\,m^{-3}$
This wood was selected because, compared to particle board, it shows very little shrinkage.
(4) Mahogany wood blocks
Thickness 23 mm
Density 560 $kg\,m^{-3}$
This wood was selected as representing an intermediate amount of shrinkage.
(5) High-pressure plastic laminate over particle board
Thickness 11 mm
Density 850 $kg\,m^{-3}$
This type of composite generally shows considerable problems at the edges and due to delamination. It is normally considered that an edge frame is required for its testing in order to suppress unrepresentative edge burning and also to hold together the layers as they become delaminated. It was also chosen for testing the new design of edge frame—since the delamination can often be violent and forceful, it must not destroy the edge frame.
(6) Extruded polystyrene foam
Thickness 50 mm
Density 26 $kg\,m^{-3}$
This rigid foam presents severe testing problems for any bench-scale test apparatus, not just necessarily heat release rate equipment.[8] This is due to the fact that the material melts prior to ignition. When it melts, the volume occupied by it is reduced by several orders of magnitude. As a consequence, what ignites and burns is not a foam of the original

configuration, but rather a thin coating on the insides of the aluminum foil used to hold the specimen.

(7) Polyisocyanurate foam
Thickness 45 mm
Density 28 $kg\,m^{-3}$
This rigid foam chars rather than melts. It was selected since an additional amount of testing data was already available from an on-going test program.[9]

(8) Flexible polyurethane foam
Thickness 50 mm
Density 23 $kg\,m^{-3}$
This material is a non-fire-retardant foam, similar to ones used for upholstered furniture cushioning, as described by Levin *et al.*[10]

(9) High-density polyethylene
Thickness 6 mm
Density 1090 $kg\,m^{-3}$
This is a high-density polyethylene containing fiberglass reinforcement, carbon black, and an ethylene-methacrylic copolymer with zinc ionomer, as used in the ASTM round robin.[4] It was selected to represent a polyolefin family polymer which does not show a tendency to melt and run.

(10) Polyvinylchloride (PVC)
Thickness 6 mm
Density 1340 $kg\,m^{-3}$
This material contains plasticizer, stabilizer, filler, and lubricant additives. It was previously used in round robin testing and was chosen because it shows a high degree of intumescence. Such intumescence requires the use of a metal grid (or equivalent means) for specimen retention. It was used to check if the new edge frame being investigated was capable of providing proper retention of the grid.

TEST RESULTS AND OBSERVATIONS

The results of the heat release rate measurements are summarized in Tables 1 and 2; these are average values for the two or three runs conducted at each test condition. The individual data curves are shown in Fig. 3 through 12; only one test run is illustrated for each figure. The temperature measurements for the reduced-size series are listed in Table 3.

Repeatability of results

Adequate information is already included about the repeatability and the reproducibility of the basic ASTM E 1354 method in the document itself;[11] thus the present study was not designed to provide additional data to this point. Hence, we will only make a few comments especially pertinent to the present investigation. It is known that polystyrene foam can often present significant difficulties in testing. Here, polystyrene foam repeatability was not out of line, showing that the difficulties there lie in apparatus dependencies, not in repeatability for *one* apparatus. For instance, for the insulated holder, associated with the mean value of 475 $kW\,m^{-2}$ for $\dot{q}''_{pk}$ is a standard deviation of 16.7 $kW\,m^{-2}$. Similarly, under the same conditions the mean time to ignition is 39.0 s, with a standard deviation of 1.3 s. The polyurethane foam, another lightweight foam product, also showed repeatability in the normal range, as developed from the interlaboratory trials.

The least good repeatability was for the polyisocyanurate foam. This difficulty in repeatability was similar with any of the test conditions (i.e. foil-only, steel edge frame, or insulated edge frame). The cause of this has not been

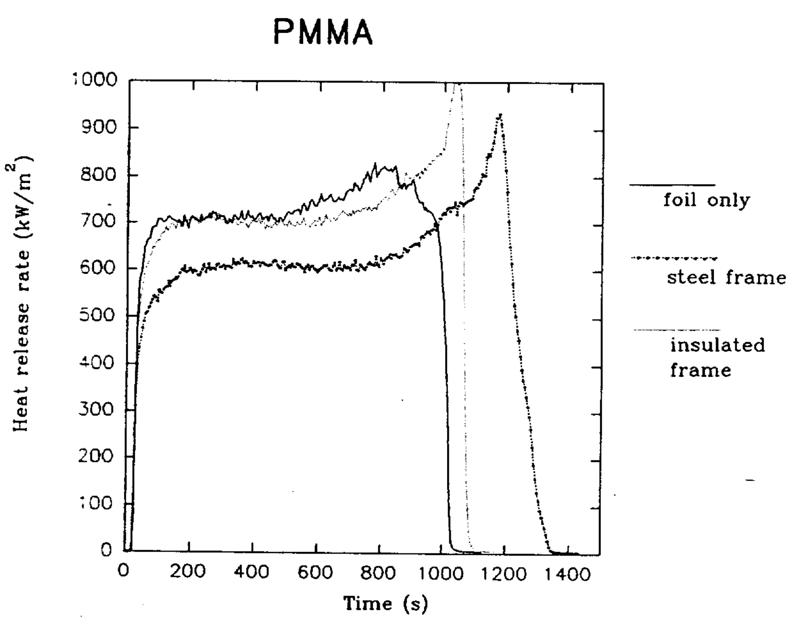

Figure 3. Results for full-size tests on PMMA.

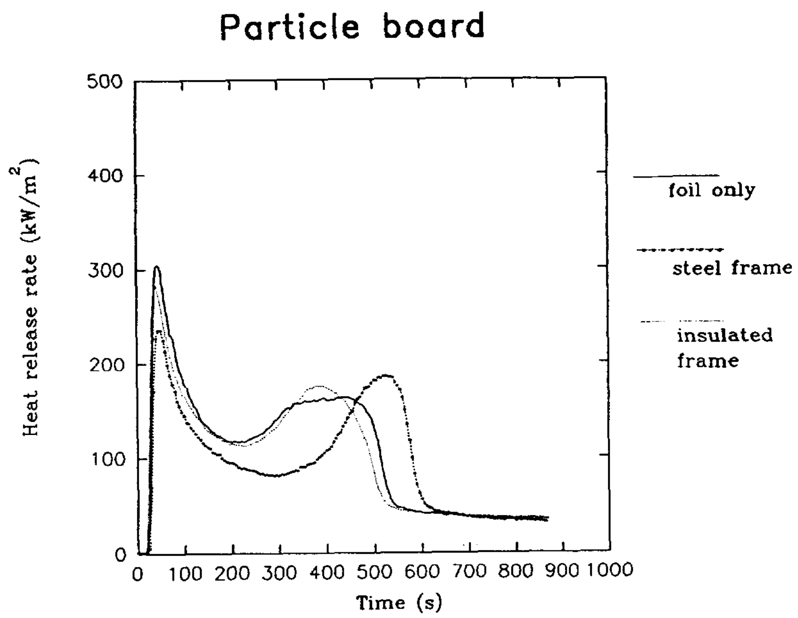

Figure 4. Results for full-size tests on particle board.

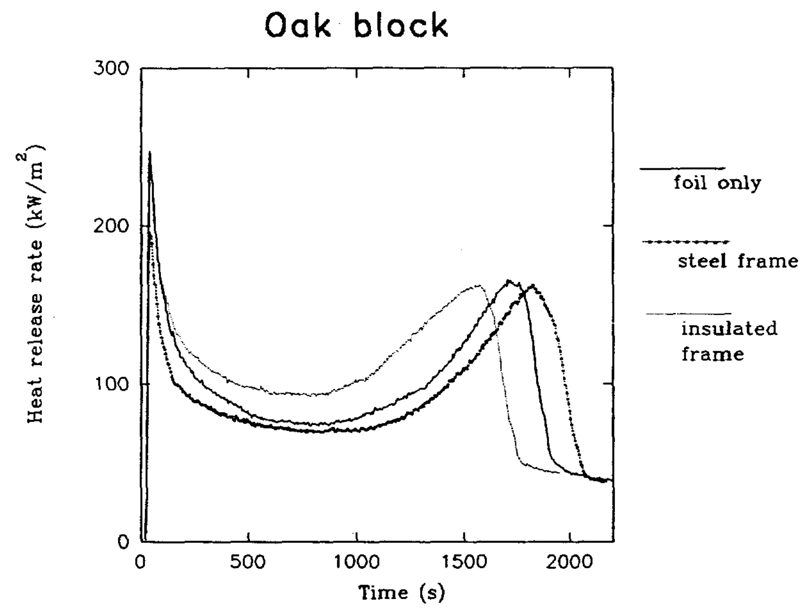

Figure 5. Results for full-size tests on oak.

determined. Figure 13 shows two sample run replicates for this material.

Observations during testing Because of the *ad hoc* nature of the way the insulated frame was machined, it was not possible to seat the specimens onto the load cell as quickly and accurately as with standard tests. As a consequence, the increase in the ignition times for this test condition may not reflect any effect associated with an insulated edge but merely operational difficulties in the experiments.

The wood materials, as indicated above, showed various amounts of shrinkage. In all cases, however, flames were anchored to the edge of the aluminum foil or the steel edge frame, rather than appearing to be attached to the edge of the specimen itself. Thus, for the specimens showing such a large amount of shrinkage that the edge frame (when used) was not able to cover the receding edge, the flame base area was the area of the available opening, and not the (smaller) area of the shrunken specimen. This was true until late in the test, when only very small, localized flamelets remained.

The polystyrene foam melted very quickly upon inserting the specimen. Eventually the vapors ignited; at this time, however, the remaining material was only a thin coating on the insides of the aluminium foil. The polyisocyanurate foam also deformed prior to igniting. It was very difficult to tell when sustained ignition occurred, and

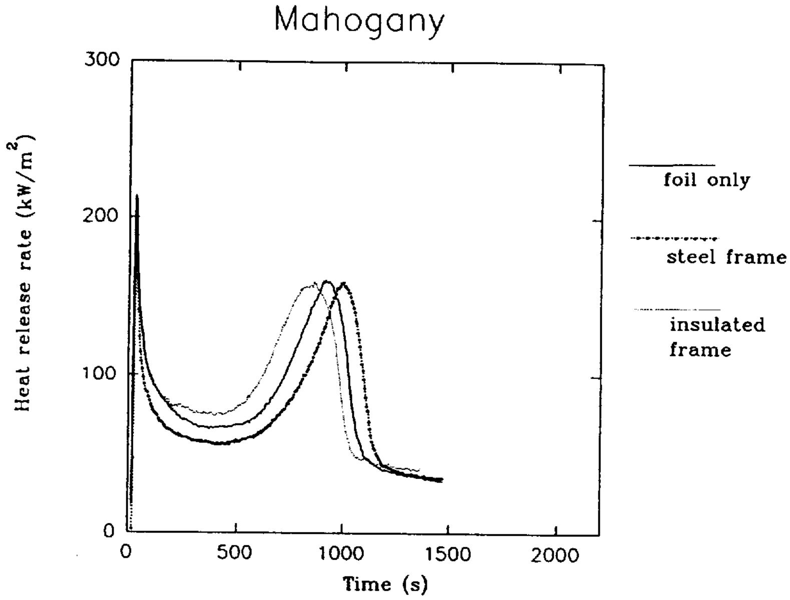

Figure 6. Results for full-size tests on mahogany.

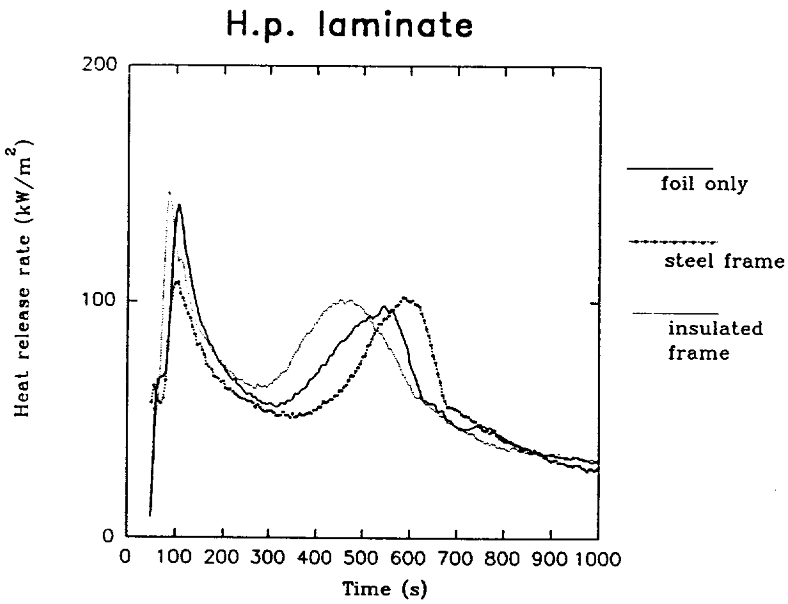

Figure 7. Results for full-size tests on high-pressure laminate.

it proved necessary to keep the spark ignitor on continuously. The PU foam, by contrast, ignited while still maintaining its original size and configuration.

With the insulating frame, the PMMA sample showed a slightly different flame shape than when burning in other arrangements. The base of the flame was not of the same width as the specimen, but, rather, 'overflowed' the edges by about 5–10 mm on each side. This is interpreted to occur because the refractory fiber material might be allowing heavy pyrolysates to re-condense at that surface. (The latter is impossible if there is no adjacent surface, as in the case of the foil-only experiments. Conversely, the cold steel frame may or may not be subject to recondensation, but any material which would condense would not be able to burn.) For the smaller, 75 x 75 mm PMMA samples, the flame shape was slightly different than for the standard size ones. The flames bend up closer to the edge, without there being as much of a visible 'boundary layer' region near the edges, where the flame would be thin and lying down.

Materials which shrink as much as does the particle board are not successfully restrained by either the steel frame or the insulated edge frame. In both cases, shrinkage was so severe that the size of the specimen became smaller than the opening in the edge frame. Once the specimen slipped out of the edge restraint, it proceeded to deform and bow some more. This is not considered to be a remediable effect, since making the edge frames more

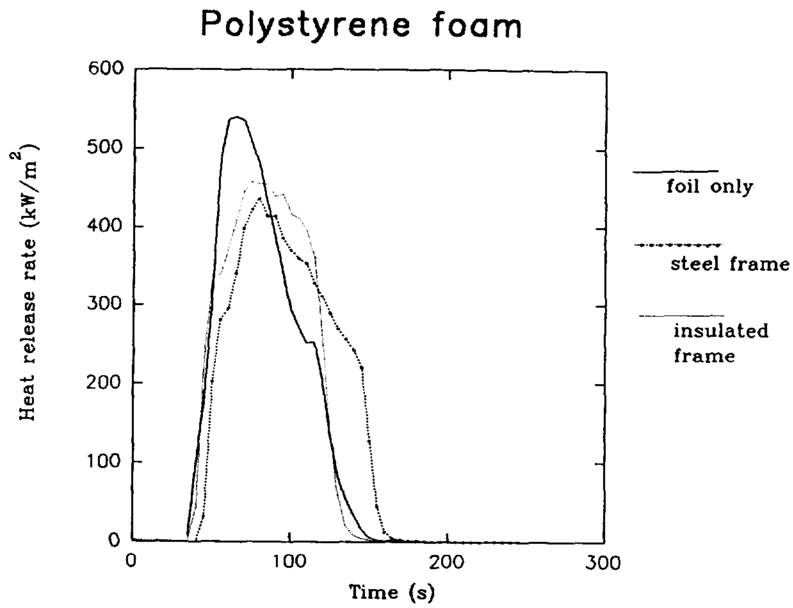

Figure 8. Results for full-size tests on polystyrene foam.

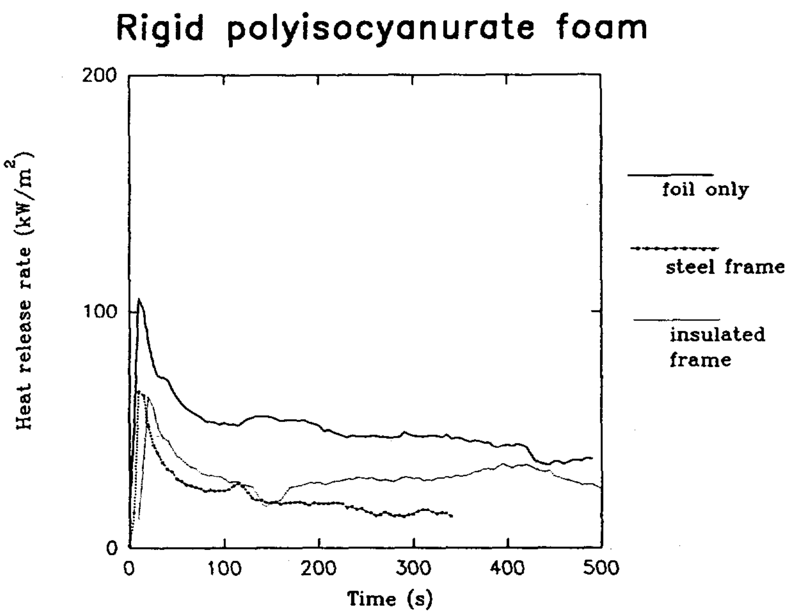

Figure 9. Results for full-size tests on polyisocyanurate foam.

intrusive upon the specimen face would be likely to cause more anomalies than to solve them.

Comparison of edge conditions

Ignition time The ignition times were not affected by the presence of a steel frame, an insulated frame, or no frame.

Peak HRR For seven out of ten materials, the peak heat release rate lined up as:

Lowest:	steel frame
	insulated frame
Highest:	foil-only

For two more materials (mahogany and h.p. laminate), a similar pattern was observed:

Lowest:	steel frame
Highest:	insulated frame; foil-only (statistically not differing)

One material—PMMA—showed a pattern:

Lowest:	foil-only
	steel frame
Highest:	insulated frame

This pattern, however, should be interpreted by careful inspection of Fig. 3. For most of the burning time of PMMA, the rank-order is: steel frame (lowest), insulated

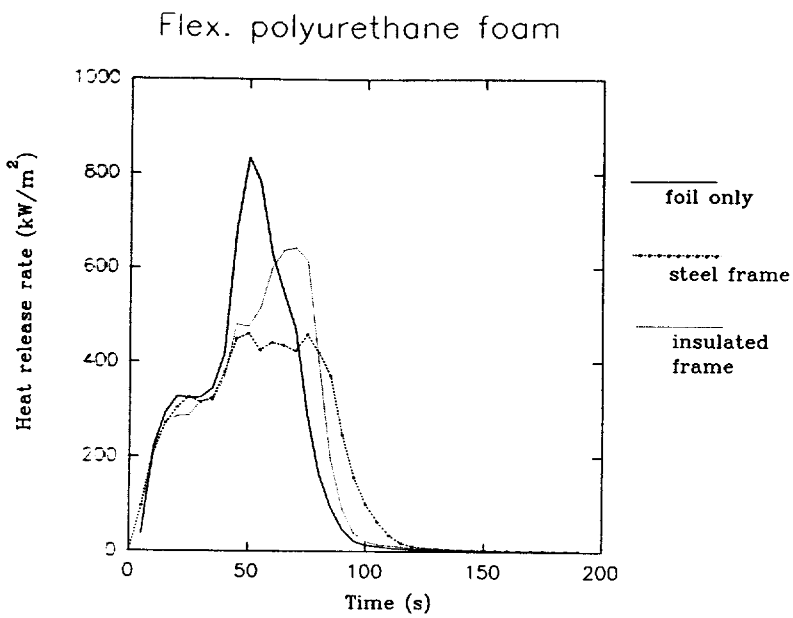

Figure 10. Results for full-size tests on flexible polyurethane foam.

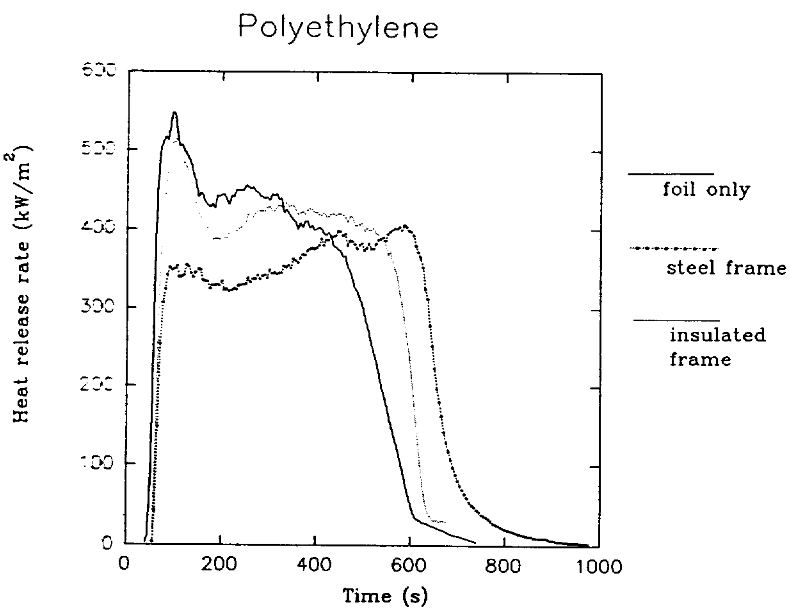

Figure 11. Results for full-size tests on polyethylene.

frame, foil only (highest). Unlike most test materials, PMMA shows its peak at the very end of the burning period. In our experience, we have noticed that this peak is associated with surface tension phenomena of the remaining globules of material as they burn out. It is *not* a phenomenon that can be extrapolated to real-scale fires (steady-state behavior should be assumed, instead). Thus, ranking of PMMA by peak value is misleading and should not be used to make any conclusions about merit of edge frames.

The results for polyethylene also require some comment. For the insulated frame and the foil-only conditions, the peak occurs near the start of the test (Fig. 11). For the steel frame, however, two peaks are seen, one early and one late; we do not have any specific explanation for this behavior.

This leaves the laminate material (Fig. 7). This material shows the ranking: steel frame (lowest), foil-only, insulated frame (highest). The difference between the insulated frame and the foil-only condition, however, is only barely statistically significant. In any case, this is a material where foil-only testing is not recommended, because of possible problems of delamination.

HRR for the 180 s period In this case, essentially all of the specimens showed the behavior:

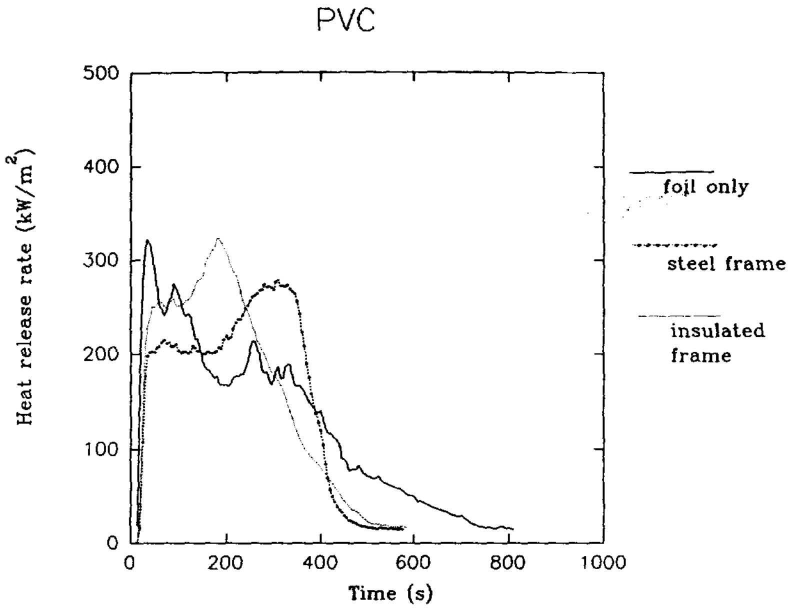

Figure 12. Results for full-size tests on PVC (note that a metal grid was used for the steel frame and the insulated frame tests, but not for foil-only tests).

Table 1. Results for full-size specimens

	Foil only			Steel frame			Insulated frame		
Specimen	t_{ig} (s)	$\dot{q}''_{pk}$ (kW m^{-2})	$\dot{q}''_{180}$ (kW m^{-2})	t_{ig} (s)	$\dot{q}''_{pk}$ (kW m^{-2})	$\dot{q}''_{180}$ (kW m^{-2})	t_{ig} (s)	$\dot{q}''_{pk}$ (kW m^{-2})	$\dot{q}''_{180}$ (kW m^{-2})
PMMA	23	827	630	24	920	524	24	994	637
Particle board	25	304	176	25	239	144	24	288	171
Oak	25	248	154	27	198	126	21	233	159
Mahogany	19	210	109	22	182	90	18	214	112
Laminate	53	133	89	52	103	73	53	144	91
PS foam	35	579	179	45	388	188	39	475	188
Polyisocyanurate foam	6	83	54	34	67	27	9	74	34
PU foam	3	801	193	2	453	191	5	675	192
PE	47	552	443	58	414	316	56	531	427
PVC	16	323	235	19[a]	258[a]	192[a]	18[a]	302[a]	232[a]

[a] A metal grid was used for the indicated tests only. No grid used for other specimens or test conditions.

Lowest: steel frame
Highest: insulated frame; foil only (statistically not differing)

Comparison with the findings of Urbas and Sand

Not surprisingly, Urbas and Sand found that, generally, the peak HRR with the steel frame was smaller than with the foil-only condition. Since part of the role of the edge frame is to suppress localized, unrepresentative edge burning, such a result is expected. What was surprising was that they reported that for several materials, the peak HRR with the insulating edge frame was higher than that with the foil-only condition. (In some other cases, the results were essentially identical.) In our tests, we do not find any significant occurrences of a behavior where the HRR results would be higher for the insulated frame than for the foil-only condition.

INTERPRETATION OF DATA

To explain the results, we must consider in detail what is happening at the sides of the specimen. When a cold specimen, wrapped only in aluminum foil, is first placed on the load cell, the temperature of the specimen and of the surroundings is essentially identical. Thus, at the sides, there is a significant flow velocity but no convective heat transfer, since for heat transfer to occur, a temperature difference must be present. The specimen is heated by the cone heater. The heater has been optimized to deliver as small a fraction as possible of its heat against the side of the specimen, nonetheless, some radiant heat does impinge on the sides. Most of this is reflected, due to the high reflectivity of the aluminum foil. A small fraction is absorbed and acts to heat the specimen. Thus, at the very start of the test there is a slight positive heat inflow into the specimen. Later during the test, the top part of

Table 2. Results for reduced size (75 × 75 mm) specimens

	Insulated frame		
Specimen	t_{ig} (s)	$\dot{q}''_{pk}$ (kW m^{-2})	$\dot{q}''_{180}$ (kW m^{-2})
PMMA	28	849	709
Particle board	21	317	188
Mahogany	21	212	118
PS foam	34	488	192
Polyisocyanurate foam	16	52	23
PU foam	3	573	175
PE	49	611	492

Table 3. Surface temperatures (°C) on 75 × 75 mm specimens in the insulated holder at 75 s

Material	Center	Midway	Edge	Ratio M/C[a]	Ratio E/C[a]
PMMA	423	442	604	1.05	1.45
PMMA	470	482	709	1.03	1.54
Mahogany	663	758	915	1.14	1.39
Mahogany	685	755	869	1.10	1.28
PE	554	586	669	1.06	1.22
PE	574	600	651	1.05	1.14

[a] Ratios of midway to center and edge to center temperature rises above 25 °C.

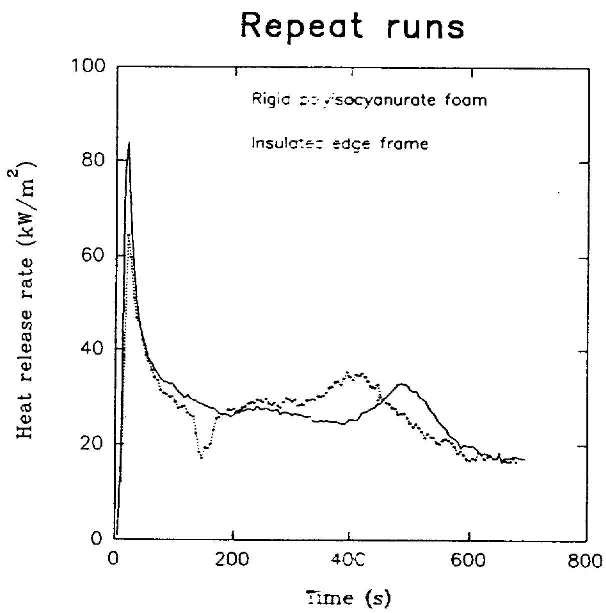

Figure 13. Repeatability of two runs for the material exhibiting the worst repeatability (polyisocyanurate foam).

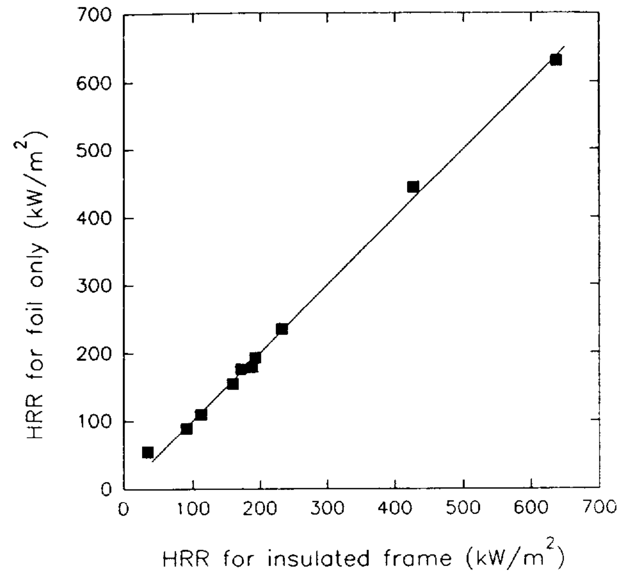

Figure 14. Three-minute average heat release rates for the foil only and the insulated holder (■ experimental data; —— equality line).

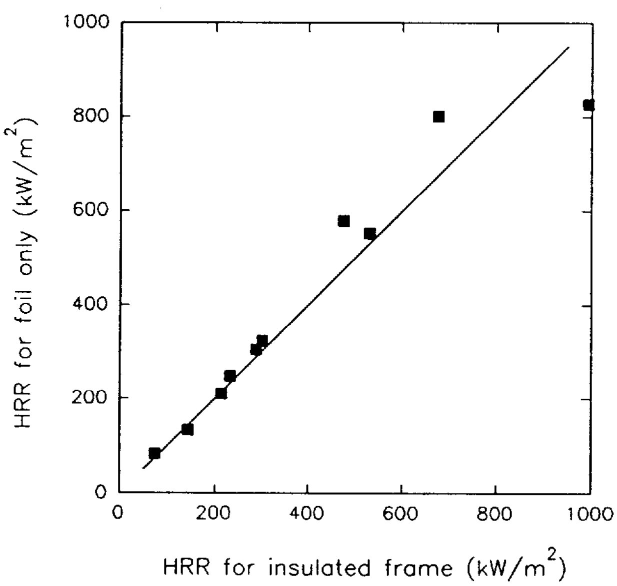

Figure 15. Peak heat release rates for the foil only and the insulated holder (■ experimental data; —— equality line).

the specimen side gets hot since it is burning. Convective heat transfer can now take place, since there is a temperature difference. This convective term is in the outflow direction. There is also a very small additional loss due to the heated foil radiating to the ambient environment; this is small because of the low emissivity of aluminum foil. The only positive term is the radiant contribution from the cone heater to the specimen's edge, but this remains at its small initial value. Thus, the overall heat flow is out from the specimen.

Consider now the case of the insulated edge frame. In this case the role of the aluminum foil can be ignored. It is important to restrict *mass* transfer, but we assume its effect is negligible on heat transfer. The insulating edge is made from the lowest-conductivity material possible, but still it represents a heat sink. Under this condition there is never any convective term present. At the start of the test, there is also no radiant heating of the sides. There is, instead, a conductive loss from the sides, which starts as soon as the specimen starts heating up. The top of the insulating collar is also being heated radiatively; since it is a good insulator, however, this effect is largely confined to a very short distance below the top and mostly does not affect the gradients along the specimen's side edge. This loss term diminishes, but does not disappear, with progressive heating later during the test.

Size effect The size effect was generally found to be small. For the reduced-size specimens, Table 3 indicates a substantive *increase* in temperature in going from the center toward the edge of the specimen. The magnitude of this increase varies from material to material. Even at the midpoint (19 mm from the edge) there is a small but significant increase over that at the center. This increasing temperature is indicative of an increasing convective heat flux as the flame approaches the surface near its edges. This effect is well known in small pool fires (see, e.g. Blinov and Khudiakov[12]) where the burning rate per unit area increases with a decrease in pan size because the perimeter-to-area ratio is becoming larger.

Whether the HRR-per-unit-area increases or decreases with changing area depends on a balance between the convective and the radiative components of heating. The convective component increases for decreasing area, while the radiative component diminishes. Thus, within the normal domain of test fire sizes (0.01–10 m diameter or width), the Blinov–Khudiakov curve of $\dot{q}''$ versus size has a minimum, then increasing for both larger and smaller diameters. This minimum is, very roughly, near the 0.1 m size of the Cone Calorimeter sample. For extrapolation of Cone Calorimeter results to larger-scale fires, it would be more convenient if the standard-specimen size were either at the trough or on the ascending portion of the curve; in that case, the extrapolations would always be monotonic. At this point, we must point to a caveat. Studies such a Blinov and Khudiakov's are able to produce a unique curve of $\dot{q}''$ versus diameter since no external radiation is considered. In a bench-scale test such as the Cone Calorimeter, where external radiation is applied, the convective/radiative balance will not be a unique function of diameter, but will be somewhat affected by the external radiation conditions.

For the present study, the HRR values for the two sizes are listed in Tables 1 and 2. For the two highest HRR materials—PMMA and PE—the HRR values are higher for the reduced-size specimens. (We again point out that the peak value for PMMA is not indicative of general performance, so we focus only on the 180 s average reading for this material.) For two foams of the three foams, the opposite situation prevails—the reduced-size specimens show smaller $\dot{q}''$ values. For the remaining materials, the results are judged not to be substantially different. Thus, we can conclude that the 75 mm size would be small enough to be on the descending part of the Blinov–Khudiakov curve for some combustibles, while not for others.

What about the standard 100 mm size specimen–is that sufficiently large not to be on the convectively dominated (descending) branch of the Blinov–Khudiakov curve? For the answer to this, we can turn to the study of Nussbaum and Östman,[13] who compared increased size (200 × 200 mm) Cone Calorimeter specimens against the standard-sized ones. Their results indicated that the larger specimens gave higher HRR values in essentially every case. Thus, we conclude that a 75 mm size would not have been optimum for standard Cone Calorimeter testing, but a 100 mm size is appropriate, since data from such specimens are monotonically related to fire scale.

The data in Table 3 show that for some materials the convective effects on the reduced-size specimen can cause a surface temperature to be larger near the edge. These are data taken only using the insulated edge frame condition. Urbas[14] has made similar measurements on specimens with a steel edge frame and found, not surprisingly, that edge temperatures were depressed.

Systematic adjustment to steel edge frame data As seen in Table 1, the heat release rates using the steel frame are significantly lower than those for the insulated frame. The data in Table 1 were computed by assuming that burning is over the full face area of 0.01 m^2 under all conditions.

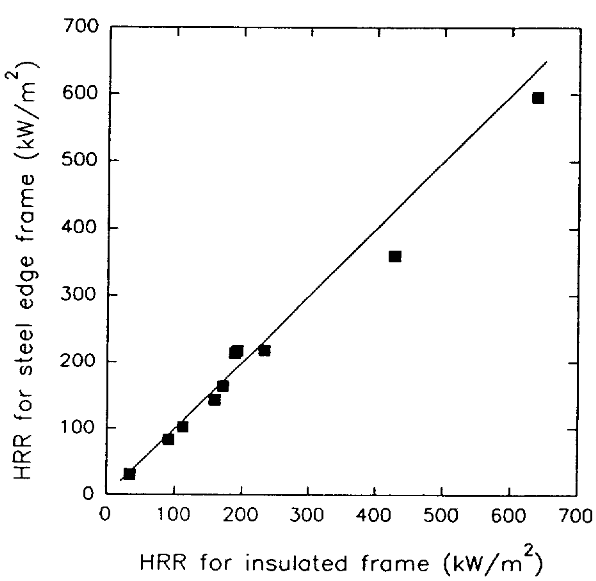

Figure 16. Calculated 3-minute average heat release rates using actual exposure area (■ experimental data; —— equality line).

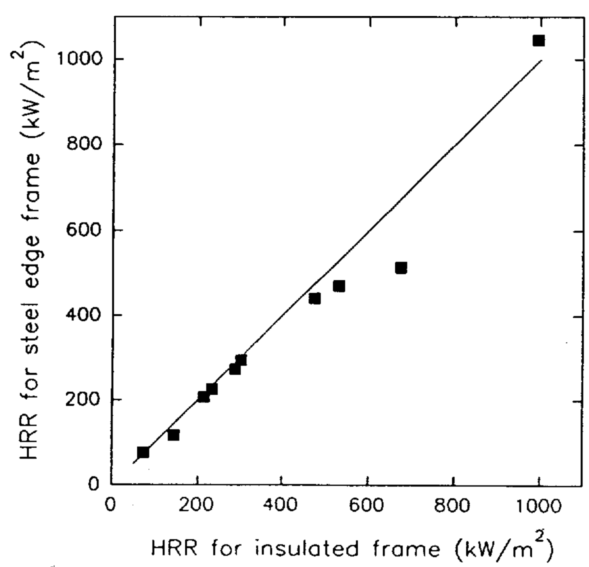

Figure 17. Calculated peak heat release rates using actual exposure area (■ experimental data; —— equality line).

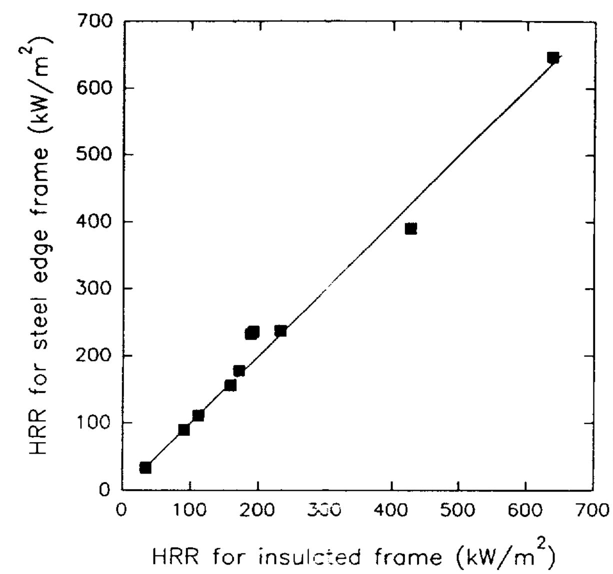

Figure 18. Calculated three minute average heat release rates using effective exposure area (■ experimental data; —— equality line).

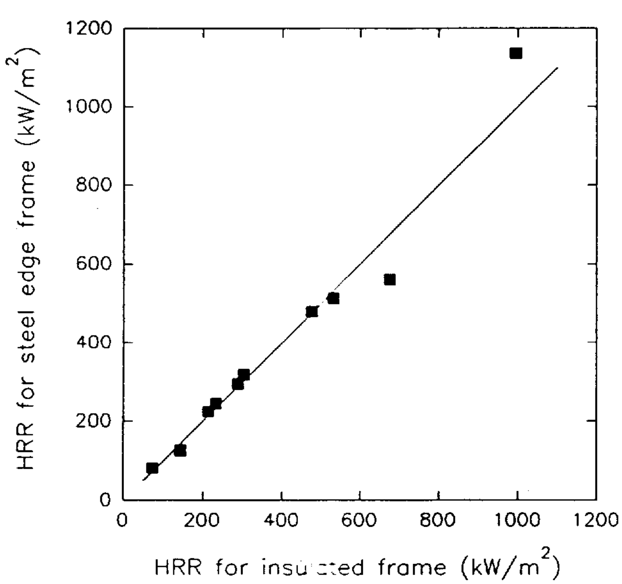

Figure 19. Calculated peak heat release rates using effective exposure area (■ experimental data; —— equality line).

This does not take into account the reduction in exposed area caused by the presence of the lip which shadows a narrow band around the perimeter of the specimen. When the heat release rates are recalculated using the actual exposed area of 0.0088 m^2 for the steel frame instead of the actual area of 0.01 m^2, the agreement is much better. This is seen in Figs 16 and 17 for the 180 s average and peak heat release rates, respectively. However, the temperature near the edge is significantly lower than that in the interior of the specimen because of the conductive heat losses from the specimen material behind the lip. Thus the rate of pyrolysis is lower in the region near the edge. This can be taken care of by assigning an empirically-derived effective exposure area of 0.0081 m^2 for the specimen. This correction provides a reasonable agreement over the range of materials as seen in Figs 18 and 19.

CONCLUSIONS

A comparison study was made using a wide range of materials—plastic and cellulosic, foam and solid, homogeneous and laminated, well-behaved and intumescent. An irradiance of 50 $kW\,m^{-2}$ was used since, our experience suggests, this is high enough to evince problematic behaviors from specimens with such tendencies but not to cause excessively fast burning. Only the horizontal orientation was used, since testing laboratories are now agreed[b] that only the horizontal orientation should be used for standard product testing. For the ten materials studied, a direct comparison was made between specimens prepared with only an aluminum foil wrapping, specimens retained by the standard steel edge frame, and specimens tested using an experimental insulated edge frame.

The essential results that were obtained can be summarized as follows:

(1) As a standard procedure, specimens which do not present difficulties such as delamination, intumescence, or edge burning should be tested with the foil only. Since it is more difficult and time-consuming to conduct tests using the edge frame, general use of the edge frame is not warranted.
(2) For specimens which require the use of the steel edge frame, the heat release rate calculated should be taken on the basis of an effective exposure area of 0.0081 m^2.
(3) The insulated edge frame is quite difficult and cumbersome to use. No evidence was obtained which would suggest that data taken with the insulated edge frame have more intrinsic validity. For specialized research purposes it may be desirable to continue exploring the applicability of data obtained with such an edge frame; for normal product testing, however, it is not a viable method.

Specifically, our experimental results do not support the finding of Urbas and Sand that an insulating edge frame is to be preferred as the standard testing technique. Also, we do not agree with Urbas and Sand that if an insulating frame is used, that its thermal conductivity and density should be matched to that of the specimen. The purpose of an insulating edge frame is to help approximate, as much as possible, an adiabatic condition at the specimen sides. This is best done by selecting as low a conductivity and density as is consistent with machinability and handling requirements. A matched-properties boundary element would only be desirable if it were also a combustible item, irradiated and burning at the same rate as the specimen; clearly this is not applicable to the present case at all.

Our conclusion from examining the data in Figs 3 through 12 is that an insulated frame might have some merit for use in situations where a steel frame is now currently being used and it is desired obtain slightly more accurate results for fire-modeling purposes. The improvement in accuracy, however, is modest in all cases. For routine, standard tests we do not consider that this slight improvement in accuracy is worth the considerably more effort required in conducting a test with the insulated edge frame. In all cases, we see no quantitative benefit to prescribing the use of an insulating edge frame for those conditions where testing is done using only an aluminum foil wrap at the present time.

The 100 mm size of the standard Cone Calorimeter specimen has been re-examined for suitability. The earlier study of Nussbaum and Östman had indicated that a 200 mm size would be needlessly large and that a specimen no greater than 100 mm should be necessary. The present study has indicated that a 75 mm specimen would be too small; thus the 100 mm size is verified.

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NOTES

[a] Manufacturers of certain products are identified in order to clarify the experimental work conducted; in no case does such identification constitute an endorsement by NIST or a statement that this material is the best suited to this purpose.

[b] A recent ballot on this issue was approved by ASTM.

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